UCRL-JRNL-210564

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March 15, 2005

Applied Physics Letters

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Ti k-alpha radiography of Cu-doped plastic microshell implosions via spherically bent crystal imaging

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(Received

ABSTRACT:

We show that short pulse laser generated Ti K-alpha radiation can be used effectively as a backlighter for radiographic imaging. This method of x-ray radiography features high temporal and spatial resolution, high signal to noise ratio and monochromatic imaging. We present here the Ti K-alpha back-lit images of six-beam driven spherical implosions of thin walled 500 micron Cu-doped deuterated plastic (CD) shells and of similar implosions with an included hollow gold cone. These radiographic results were used to define conditions for the diagnosis of fast ignition relevant electron transport within imploded Cu-doped coned CD shells.

Radiography using nanosecond pulses of thermally generated soft x-ray emission from high temperature laser produced plasmas was developed for pulsed[1] and streaked[2] backlighting of laser driven implosions and observation of fluid instabilities.[3] It is now an important diagnostic widely used to record hydrodynamic phenomena of all kinds in laser driven targets. In typical state of the art measurements, gated channel plate imagers give 50 to 100ps time resolution. With multi-kilojoule laser energy the sources are bright enough for radiography at photon energies approaching 10keV, but are ineffective at higher photon energies due to rapidly decreasing brightness.[4]

We present a demonstration of radiography of an implosion using a non-thermal K-alpha radiation source generated with a high intensity ultra-short laser pulse. This technique gives more than a 10-fold improvement in time resolution and readily achieves the brightness required for high definition radiography. Conversion efficiency measurements with sub–joule short pulse lasers and Monte Carlo modeling[5] suggest the source is scalable to 100keV, giving a potential capability to penetrate up to 1000x more matter than thermal plasma radiography. The enhanced penetration promises to be vital for radiography of the more massive and dense implosions produced by the megajoule-class lasers and Z-pinches which will be used to demonstrate thermo-nuclear ignition in inertial confinement fusion research.

The diagnostic was implemented using an 81J, 800fs 1053nm Nd:glass laser pulse.[6] The beam was focused by an f/3 off-axis parabolic mirror. An out of focus plane was chosen producing a 440 x 750μm^2 full width at half maximum (FWHM) elliptical spot on a 25μm thick Ti foil with an average intensity of 3.1×10^{16} W/cm^2. The laser interacted with the foil to produce an extended backlighting source of K-alpha x-rays.[7]

This source was located 4mm from the target and irradiated on its side opposite the target. The target was a 500μm diameter, 7μm thick CD polymer shell Cu doped at 0.7 atomic percent. Some targets included an inserted hollow gold cone used as the conduit for the ignitor beam in fast ignition studies.[8] The implosion was produced with six 10.8cm diameter orthogonal drive beams each delivering 157J, 1ns Gaussian pulses at 1053nm and focused at f/2.5 with their marginal rays tangential to the shell. A 1.6cm aperture SiO_2 2023 quartz crystal bent to a radius of 38cm and operating at 1.0° off normal incidence imaged a plane centered in the backlit implosion. It produced a 7.9x magnified image onto a Princeton Instruments TEK1024x1024DBT3, 1 square inch, 1024x1024 pixel charge coupled device (CCD) internally cooled to −30° C. Astigmatism and spherical aberration limit theoretical spatial resolution to 10μm.[9] At 7.9x magnification, 10μm resolution corresponds to 3 pixels. The images have therefore been smoothed over 3X3 pixel areas without significant loss of information. This smoothed pixel limited resolution of 9.6μm convolved with the 10μm theoretical spatial resolution results in a resolution of 13.9 μm. Systematic errors such as a slightly defocused CCD and crystal mosaic effects combine to further lower the resolution.

The absolute yield of K-alpha photons was measured using a single hit CCD spectrometer and the spatially resolved absolute brightness of the source was determined by comparing the integrated counts in the images of the source with the absolute number of photons. Details of the absolute K-alpha measurement are discussed elsewhere.[7] The source brightness was 4.2×10^{13} photons-cm^{-2}-sterad^{-1} and the collection angle of the imaging diagnostic is 4.4×10^{3} sr. Very high temporal resolution of ~1ps resulted from the 800fs pulse in the backlighting beam.[5] Various phases of implosion were imaged by delaying the backlighting beam with respect to the driver beams. The timing was jitter free since the long pulse implosion drive was obtained by further stretching and amplification of a fraction of the uncompressed chirped pulse.[6] Figure 1a shows a backlit image of an un-irradiated shell. Limb darkening is clearly seen together with a glue blob attaching the support fiber. The limb transmission minimum was measured from the lineout in figure 1b to be 85%. A theoretical transmission profile of the 500μm diameter, 7μm thick shell yielded a transmission minimum of 75%. The effect of finite resolution was determined by convolving this theoretical profile with a Gaussian kernel. The calculation uses shell density and opacity of $1.03 g/cm^3$ and $23 cm^2/g$, respectively. Adjustment of the FWHM of the Gaussian to match the 85% observed minimum yields an effective resolution of 20μm.

The image has a maximum counts per pixel of 18,000. With ~22eV/count and 4.5keV photons, this corresponds to an average of ~81 photons/pixel or a signal to noise (S/N) ratio of ~9:1 in the raw images. Smoothing of the image into 3x3 pixel areas enlarges the region over which the statistical count is made resulting in the observed S/N ratio of about 27:1 as shown in figure 1b. A shell at maximum compression (3.25ns after drive peak) is shown in figure 2a. Here the back-lighter source size has been increased to $420 \times 750 \mu m^2$ and the peak brightness is reduced to 5.2×10^{13} photons-cm^{-2}sterad^{-1}. In figure 2b, a lineout of the implosion core absorption pattern reveals a 96μm diameter FWHM. A similar image of an implosion incorporating a 30° Au cone positioned with the cone axis 51° from the radiographic axis is shown in figure 3. The FWHM core diameter is 119μm. The tip face of the cone is 5±2μm thick with a 40μm outer diameter. The opening angle appears significantly larger than 30° due partly to the 51° viewing angle which increases the apparent angle to 38.4°. The much higher observed angle of 85° indicates an additional increase attributable to ablation of Au from the cone by thermal x-rays.[10]

Images from a sequence of timings show a smooth implosion from a 500μm shell through the 96μm stagnation at 3.25ns followed by expansion to 104μm at 3.5ns. Diameters are defined as the FWHM of attenuation. Measurement error was determined by the 20μm resolution, which increases the apparent diameter, combined with 27:1 S/N which contributes a random error. Shell diameter vs. short pulse delay reveals an average implosion velocity of $6.0\text{x}10^4$ m/s. We have compared our results to one-dimensional simulations using Hydra[11] of a 7μm thick 500μm diameter plastic shell with a low density ($1\text{x}10^{-5}$ g/cm^3) gas fill irradiated by a 1.0 ns 800J Gaussian laser pulse. To simulate the effect of hot-electron preheat we directly deposited energy into the shell. With 5J of absorbed preheat we find a peak implosion velocity of $7.0\text{x}10^4$ m/s and an 80μm diameter stagnated core 2.5ns after the peak of the pulse. The modeled implosion trajectory is co-plotted with the observed trajectory in figure 4a. The 17% shorter time to peak compression in the model indicates that the 1D approximation of a range of ray directions used to represent the six beam tangential overlap of the drive beams, overestimates the drive.

The opacity of the imploded shell is a function of its temperature and density. Data from the Sesame tabulations show that over an expected range of temperature and density, the opacity for 4.6keV radiation is approximately invariant at 43cm^{2}g^{-1}. Intensity line-outs of implosion cores were processed to obtain transmission profiles by comparison to unattenuated intensity profiles. The form of the unattenuated profiles was determined to be nearly Gaussian. Shot to shot profile estimations were based on an interpolated fit to the backlighter lineout (fig. 2b). This transmission data was Abel inverted to obtain a density profile as shown in figure 4b. As an estimate of the calculated density error, multiple inversions were performed for various backlighter profiles within the range of their uncertainty (fig.2b). The peak compression density rises quasi-linearly from the zero density edge to $4 \pm 0.25 g/cm^3$. Also shown in figure 4b is the Hydra-predicted density profile (with 5J of preheat) at maximum compression showing a peak density of 3.75 g/cm^3 (compared to 45 g/cm^3 without preheat)

In conclusion, it has been demonstrated that ultra-intense laser driven Ti K-alpha monochromatic backlighting and imaging is a viable radiographic diagnostic for characterization of laser driven implosions.

This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48. We acknowledge R. Clarke, M. Notley, R. Heathcote, D. Neville, P. Brummitt, M. Tolley and D. Neely for their technical support of the experiment.

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Figures:

FIG. 1. (a) K-alpha radiographic image of un-imploded 500μm polymer shell. (b) Horizontal lineout (indicated by the horizontal line through the image 1a) reveals an average intensity of 18,000 counts.

FIG. 2. (a) K-alpha radiographic image of polymer shell at peak compression. (b)Vertical lineout (indicated by the vertical line through the image 2a) shows the fully compressed core. Also shown is the range of interpolated backlighter intensities used in the density calculations.

FIG. 3. Cone implosion radiograph at 3.25ns after drive peak shows 119μm diameter stagnated core near tip of 30° Au cone. Outline indicates 51º oblique view.

FIG. 4. (a) shows shell radius as a function time after drive peak and (b) indicates core density as a function of radius at peak compression. The solid lines are experimentally obtained and the dotted lines are results of the 1-D Hydra code.

Figure # 1

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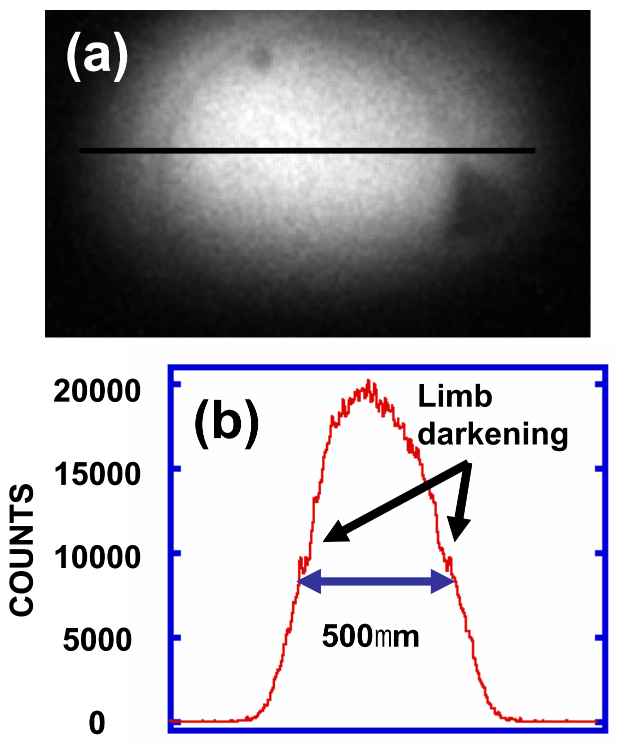

Figure # 2

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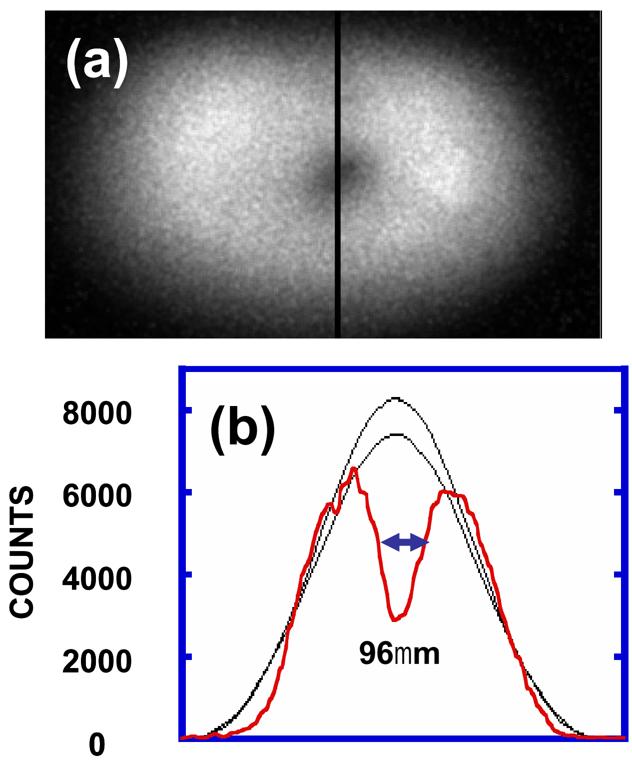

Figure # 3

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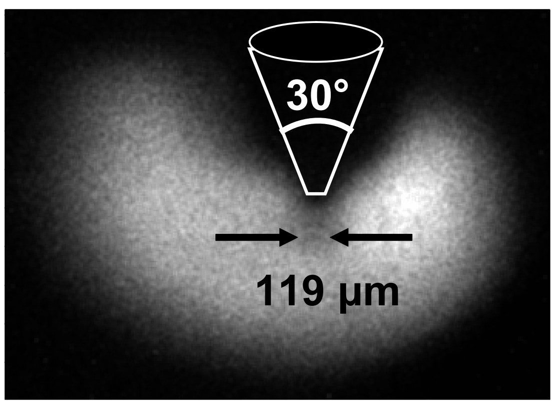

Figure # 4

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